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NAVORD REPORT 1818

AN EXPERIMENTAL STUDY OF THE FEASIBILITY OF MEASURING THE SURFACE TEMPERATURE OF A PROJECTILE IN FLIGHT BY MEANS OF ITS THERMAL RADIATION

28 May 1951

U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

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NAVORD Report 1818

AN EXPERIMENTAL STUDY OF THE FEASIBILITY OF MEASURING THE SURFACE TEMPERATURE OF A PROJECTILE IN FLIGHT BY MEANS OF ITS THERMAL RADIATION

Prepared by:

L. G. Mundie and P. W. Shadle

ABSTRACT: A series of preliminary measurements are described which are designed to determine the feasibility of measuring the surface temperature of a 30-caliber projectile in flight by means of its thermal radiation. The images of a series of the projectiles are allowed to cross the sensitive surface of a lead sulfide photoconductive cell, the resulting signals being observed with an oscilloscope. The measured pulse heights are plotted against the corresponding temperatures of the blackened surface which forms the background for the projectiles, in the form of a "working curve". The temperature of succeeding projectiles may be determined, in principle at least, with the aid of this curve together with a measurement of the signal produced by them upon crossing a background of known temperature. Three working curves of this type are presented, obtained under slightly different experimental conditions. With the detector used, these curves seem to indicate that the method cannot be used in the case of projectiles with temperatures below 150°C; above this temperature the data so far obtained indicate a probable error of about ±10°C in the measurement, provided no systematic error of an unknown nature exists in the method. It is hoped that improvements in the measuring technique will increase this accuracy, at least at higher temperatures.

U. S. NAVAL ORDNANCE LABORATORY
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This report describes a preliminary experimental study designed to determine the feasibility of measuring the surface temperature of a projectile in flight by means of its thermal radiation. The work was performed under task NOL-Re9a-108-1. The authors wish to express their appreciation to Mr. V. Halbmillion who suggested the problem and participated in many helpful discussions regarding the problem. They are also grateful to Dr. W. W. Scanlon for suggesting the method of measuring temperature used in this study. The study of the various blackening techniques was carried out under his supervision. While the results reported are of a preliminary nature, it is felt that they may be used as a basis for a later, more detailed study of the problem.

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Rear Admiral, USN
Commander

Leslie W. Ball
LESLIE W. BALL
By direction

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ILLUSTRATIONS

REFERENCES

(a) NOLM 10830 "Temperature Measurement with Lead Sulfide Cells" 20 March 1950.

(b) NOLM 10326 "Apparatus for Time Constant Measurements of Photoconductive Cells" of 7 July 1949.

AN EXPERIMENTAL STUDY OF THE FEASIBILITY OF MEASURING THE SURFACE TEMPERATURE OF A PROJECTILE IN FLIGHT BY MEANS OF ITS THERMAL RADIATION

INTRODUCTION

1. The temperature of the surface of a projectile in flight has long been a topic of considerable conjecture. No satisfactory method has been devised to date, however, for the measurement of this quantity, except possibly in the case of projectiles sufficiently large to carry measuring equipment. The development of the photoconductive cell, which combines a high sensitivity with an extremely short time constant, has introduced the possibility of utilizing the thermal radiation from the projectile to determine its temperature. Reference (a) describes a few preliminary experiments performed at the NOL, designed to determine the accuracy with which a PbS cell can measure the surface temperature of both stationary and rapidly moving objects by means of their thermal radiation. The present memorandum will describe a series of experiments performed with essentially the same equipment, designed to determine the surface temperature of a 30-caliber projectile in flight.

PRINCIPLE OF THE EXPERIMENT

2. One of the fundamental assumptions, on which the present measurements are based, is that the response of a lead sulfide detector to the thermal radiation from a heated object of emissivity different from zero will increase in a monotonic fashion as the temperature of the source is raised. Since the response of a detector of this type is very nonuniform with wavelength, the total response will not at all obey the fourth-power radiation law. That the response is a monotonic function of the source temperature is, however, to be expected. (See, for example, reference (a)).

3. The experimental procedure followed during the present measurements is to observe on an oscilloscope the signal generated by the lead sulfide detector when the image of the projectile to be studied crosses its sensitive area, momentarily replacing the image of a heatable background. A schematic diagram of the optical arrangement is shown in Figure 1. Here it may be seen that the projectile is fired past a heatable background surface so arranged that as it passes a certain portion of its flight it is momentarily imaged on the lead sulfide cell by a concave mirror. Prior to and immediately following this instant, the heated surface is itself imaged on the detector. The latter image is actually somewhat diffuse, as the heated surface is somewhat farther from the mirror than the

projectile; since it constitutes a uniform, extended source, however, this diffuseness has no effect on the signal strength. Further details regarding the experimental arrangement will be given later.

4. Let us assume for the moment that the surfaces of the projectile and of the background have equal emissivities, and that all surrounding objects are at room temperature. Utilizing the assumption of paragraph 2, we should expect a "positive" or "negative" pulse on the oscilloscope screen depending on whether the temperature of the projectile is higher or lower than that of the background. If the temperature of the background can be made exactly equal to that of the projectile, a flat trace (pulse of zero height) should result. In this way the usual advantages of a null method can be secured.

5. In practice, of course, this ideal case generally cannot be realized, since the exact temperature of the projectile under study cannot be predicted beforehand. Suppose, however, that a series of "calibration" projectiles are fired under identical conditions, and that these projectiles all possess the same temperature as they pass the measuring station. If the background temperature at the beginning of the series is, say, room temperature, and is raised slightly between the firing of each successive member of this series, the signal produced will vary in a continuous manner. Plotting the heights of the pulses obtained as a function of the corresponding background temperatures yields a smooth curve which we will refer to as a "working curve". Figure 2 (a) presents qualitatively the general appearance of a typical working curve of this type. In this figure typical signal pulses are indicated by arrows. It is seen that the "sign" of the pulses changes from positive to negative as the background temperature is raised from values below that of the projectiles to values above the projectile temperature.

6. In order to bring out the usefulness of a working curve of this type for the determination of the temperature of subsequent projectiles, let us consider a convenient property to be expected of the signal pulses obtained in this experiment. One would expect the pulse obtained when a projectile of temperature t_1 crosses a background of temperature t_2 to be of equal magnitude but of opposite sign from that obtained when a projectile of temperature t_2 crosses a background of temperature t_1. This wil only be true when the emissivities of projectile and background are equal, and when no other experimental parameter is changed between measurements.

7. Utilizing this property of the signal pulses we may replot the working curve in the manner shown in Figure 2(b) where the shape of the curve is unchanged from 2(a), but the directions

of the pulse "arrows" have been reversed, and the words "background" and "projectile" have been interchanged. Plotted in this way it is seen at once that a quite new significance may be attached to the working curve described above. It may be used directly, in principle at least, to determine the temperature of a subsequent projectile; one has only to measure the signal pulse of the latter against a background possessing the temperature for which the pulse height was zero with the calibrating projectiles. The temperature of the projectile in question can then be read directly from the graph shown in Figure 2(b). If, finally, the overall system responds linearly to the incident radiation (no "overloading"), Figure 2(b) can be still further modified so as to make it useful for background temperatures other than that specified above. This modification is indicated in Figure 2(c), where the pulse heights to be expected upon selecting a different background temperature are indicated. From a curve of this type the temperature of a subsequent projectile can be determined directly for any background temperature. The remainder of this report will be devoted mainly to a description of the experimental determination of working curves of this type.

EXPERIMENTAL DETAILS

8. The measurements were performed in the Aerodynamics Range at NOL. The detecting equipment was placed about fifteen feet from the muzzle of the gun. A photograph of the assembled equipment is presented in Figure 3. In Figure 4 the optical arrangement is shown in greater detail.

9. A standard 30-caliber rifle was used to fire the projectiles, the speed of which was approximately 2700 feet per second. The rifle was mounted by its barrel in two tight-fitting solid steel cylinders. These cylinders rest in a heavy steel V-shaped support. The muzzle of the gun enters a multiple baffle chamber which serves to trap many of the smoke particles emerging from the muzzle and to reduce greatly the accompanying sound. This arrangement may be seen at the left in Figure 3.

10. The mirror used for imaging the projectile on the detector is spherical, front-aluminized, with a radius of curvature of 12 inches, and a diameter of 11 inches. It may be noticed in the photographs of Figures 3 and 4 that the center portion of the mirror has been removed; this removal was performed during a previous experiment, the opening having no effect in the present measurements except to reduce the signal slightly. The mirror was mounted in a double gimbal so as to permit thumbscrew adjustment about both vertical and horizontal axes. The distances of detector and projectile from the center of the mirror during measurement were approximately 10 and 14 inches, respectively. A somewhat diminished image of the projectile thus crosses the detector during the measurement.

11. A PbS cell of the evaporated type manufactured by Photoswitch, Inc., was used as a detector. Its time constant, as measured in the manner described in reference (b), was about 3 microseconds. In common with most detectors of this type, its spectral sensitivity was peaked at about 2 microns, and it was insensitive to radiation of wavelength greater than about 3.3 microns. The sensitive area was 0.36 mm wide and 6.4 mm long.

12. The cell could be mounted so that the length of the sensitive area was either parallel to or perpendicular to the path of the projectile. In Figure 5 is presented a schematic diagram, drawn to scale, of the arrangement in the latter case. Here the image of the projectile is seen crossing the sensitive area of the PbS detector. The strength of radiation signal received by the detector at any instant is proportional to the area covered by the image of the projectile, assuming the sensitivity of the cell to be uniform across its surface. In the present case a constant area of the cell is filled after the tapered front portion of the projectile has crossed the cell, assuming that all the projectiles traverse the same line of flight and that their axes remain parallel to the line of flight. Scattering, yawing, or precessing of the projectiles during flight would introduce errors, but at the close ranges used in the present experiment these effects are rather small. This was checked occasionally during the measurements by mounting a piece of paper in the path of the projectile at a point adjacent to the measuring equipment and examining the holes formed by the projectile. In subsequent measurements at greater ranges, where dispersion of the projectiles may become a problem, it may be desirable to use an optical arrangement in which the length of the electrodes is considerably larger than the image of the diameter of the projectiles. With this arrangement the sensitivity of the method will be decreased (since only a portion of the sensitive area of the detector will be utilized), but a considerably greater amount of scatter of projectiles will be tolerable.

13. The flat surface of an ordinary electric "hot plate" was used as a background surface for the first series of measurements. A thermocouple was soldered to the surface in order to measure the surface temperature. During later measurements the "background" was constructed in a special manner in an effort to reduce the effect of reflection from the front surface of the projectile. For this purpose the projectile was fired along the axis of a cylindrical furnace provided with an opening in the front wall to permit the radiation emitted by the projectile to reach the mirror. This furnace may be seen in Figures 3 and 4. A thermocouple was again used to measure the temperature of the background surface, which in this case was the inside surface of the back wall of the cylinder.

14. As indicated earlier, one of the basic assumptions of the measurement is that the spectral emissivity of the projectile is equal to that of the background. It is also desirable to have both of these emissivities as high as possible. To this end, the projectile and the background were both coated with the same blackening material. Considerable experimentation was performed in an effort to find a coating which would withstand the mechanical and thermal shocks associated with firing. The latter characteristic was tested by examining coated projectiles after test-firing into a tank of water from which they could be recovered easily. Chemically deposited blacks of platinum, arsenic, and antimony were tried but were generally found not to withstand the rigors of firing satisfactorily. A coating of commercial India ink, however, stood the test rather well. The emissivities in the PbS spectral region of several sample coatings of this material were then measured for source temperatures ranging from 50°C to 100°C. The measured values ranged from 0.86 to 0.95. This material thus appeared to present a satisfactory combination of characteristics; consequently the surfaces of both the projectiles and the background were coated with it during the measurements described in this report.

15. The electrical signal from the PbS detector was first fed into a preamplifier having a gain of 20 db and a band pass extending from 800 cps to 1 mc. This preamplifier was designed and constructed at the Naval Ordnance Laboratory. The preamplifier was followed by a Hewlett-Packard Model 450-A amplifier with a gain of 40 db and a band pass extending from 10 cps to 1 mc. The output of this amplifier was fed into a Tektronix Oscilloscope, Model 511-A. These units are identified in Figure 3. A horizontal sweep speed of 0.1 cm per microsecond was used on the oscilloscope. The signal pulse on the oscilloscope screen was photographed with a Bolsey 35 mm camera, using a speed of f/2.9 and Linagraph Ortho film.

16. In order to obtain reliable synchronization of the oscilloscope sweep with the projectile, a narrow strip of tinfoil was mounted in the path of the latter a short distance in front of the furnace. (The tinfoil may be seen in Figures 3 and 4.) This strip was connected in the trigger circuit in such a way that when the projectile broke the strip, the opening of the circuit initiated the sweep.

RESULTS

17. Three series of measurements were made, each designed to obtain a "working curve" of the type described above, but each made with a slightly different experimental arrangement. In all cases standard projectiles from the 30-caliber rifle were used. In series (a), the hot-plate was used as a background, and the electrodes of the PbS detector were aligned perpendicular to the line of flight of the projectile. In series (b) the cylindrical furnace was used to form a background, the electrodes remaining

perpendicular to the line of flight. In Series (c), the furnace was again used as a background, but the electrodes of the detector were parallel to the line of flight. With the electrodes perpendicular to the line of flight one would expect to obtain a more distinct separation of the signals from the front and rear portions of the projectile.

18. Figure 6 presents a typical series of signal pulses obtained, corresponding to a series of background temperatures. These particular traces were obtained in the (b) series referred to above. The time of transit of any point of the projectile across the detector in this case is about 0.5 microseconds. Since this is considerably less than the time constant of the PbS cell (3 microseconds), one cannot expect to obtain very detailed information with respect to the rate of variation of temperature across the surface of the projectile. On the other hand the time of transit of the entire projectile across the detector is about 40 microseconds; this is sufficiently long that one would expect to obtain some structure of this type. It may be seen, for example, that the pulses generally consist of two distinct components each of which changes progressively as the background temperature changes. Using the gridwork on the face of the oscilloscope as a "landmark", it is possible to associate the various portions of the trace with the corresponding portions of the projectile; it is possible, for example, to identify one of these components even in the absence of the other. A small amount of random lateral displacement may be observed in passing from one trace to the next. This is probably due to imperfections in the triggering arrangement. With a room-temperature background a positive pulse is obtained from the rear portion of the projectile, but no signal is obtained from the front portion. As the background temperature is raised above 150°C a negative pulse is obtained from the front portion of the projectile, that from the rear portion remaining positive until a background temperature of about 240°C is obtained. Thereafter both pulses become negative and somewhat unresolved, the second pulse appearing merely as a point of inflection on the combined trace. In Figure 7 are plotted the working curves obtained in series (a), (b) and (c) from traces similar to those shown in Figure 6. In obtaining these curves the peak values of the traces were used where a clear peak existed. In some cases the rear portion of the projectile gave only inflection to the trace. The point at which this inflection occurred was then estimated and used in the working curve.

DISCUSSION

19. It is seen from Figures 6 and 7 that the rear portions of the projectiles appear to possess a higher temperature than the front portions. This is not surprising, since if one examines a projectile that has been fired in the manner used during these

measurements, one finds that a thin surface layer has been scraped away from the rear portion by the rifling of the barrel. One would expect a rather intense local heating to be associated with this so-called "engraving" of the rear portions of the projectiles. Since the station at which these measurements were made was only 15 feet from the muzzle of the gun, very little of this heat would have time to flow into the interior of the projectile. The rear portions give rise to positive signals until the background temperature has been raised to 240°C. Since these portions, being freshly engraved, would be expected to have a rather low emissivity we must conclude that their actual temperatures are considerably in excess of this figure. Since the emissivities of the engraved portions of successive projectiles might be expected to fluctuate rather widely, it is not surprising to find a large "scatter" of the corresponding experimental points as seen in Figure 7. These points are, however, only of passing interest at present.

20. The experimental points corresponding to the front portions of the projectiles seem to define a fairly reliable working curve in series (a) and (b). In series (c) the scatter is rather great; this may be due to the considerable overlapping of the signals from the front and rear portions inherently associated with the orientation of the detector used in this series (electrodes parallel to line of flight). As mentioned above, no signal is obtained from the front portions of the projectiles for background temperatures less than 150°C, above which temperature negative pulses are obtained. We may then conclude, following the reasoning outlined in paragraph 4, that the corresponding surface temperature is less than 150°C. No further conclusions can be drawn regarding these temperatures. This then, is at once seen to be one of the limitations of this method of measurement -- surface temperatures below 150°C cannot be measured in this manner with the detectors presently available. This result is in agreement with the result of a preliminary experiment designed to test the feasibility of the method and reported in reference (a). In this experiment the projectile was simulated by a solid wire (at room temperature) attached to the periphery of a wheel. The wheel was rotated at such a speed that the time of transit past a heated background was approximately the same as that of the projectile in the present experiments. Here, too, the signal pulse obtained for background temperatures below 150°C was considered unusable. Above this temperature, however, the accuracy of this method rapidly increased (see Fig. 7 of reference (a)); this is again in agreement with the present measurements, since the experimental points of series (a) and (b) of Figure 7 appear to establish a rather definite working curve for temperatures in excess of 150°C. The degree of scatter of these experimental points would seem to indicate a probable experimental error of ±10°C in this region provided there exists no systematic error of an unknown nature.

21. Having established that the blackened front portions of the projectiles used here produce no signal for background temperatures below 150°C, it is interesting that one would expect no change in the appearance of the working curve of projectiles of this temperature upon omitting the black coating or even upon polishing the projectiles, provided all surrounding objects are at room temperature. This latter condition was approximately fulfilled during series (a), when the hot plate was used as a background. A few traces were observed during this series with polished projectiles, the hot plate being left black. The corresponding points indeed fell directly on the working curve shown in Figure 7, within experimental error. During series (b), when the cylindrical furnace constituted the background, the abovementioned condition was obviously not fulfilled, since there exists the possibility of reflection from the surface of the projectile of radiation emanating from regions of the furnace bordering the "window" aperture. One would expect a reduction in signal due to this effect. A few polished projectiles were fired during this series to check this point. The signals obtained in this case did fall somewhat below those shown in Figure 7, as was expected.

22. Bearing in mind the results of the preceding paragraph, it is perhaps worthwhile to comment here on the relative merits of the cylindrical furnace and the plane hot plate for use as backgrounds. If the emissivities of background and projectile can be made accurately equal, and if all surrounding objects are at room temperature, the plane hot plate is preferable, since only in this case does the interchanging of projectile and background temperatures result in the reversal of the sign of the pulses with no change to be expected in amplitude. If, however, the emissivities cannot be made equal, the furnace type of background is to be preferred, since in this case one would expect the "cross-over" point (corresponding to pulses of zero height) to occur more nearly at the point when the temperatures of projectile and background are most nearly equal - the errors due to reflection of room temperature radiation from the surface of the projectile being minimized.

23. If, now, projectiles were available which possessed surface temperatures in excess of 150°C, one of the working curves of Figure 7 could be used to determine their temperatures following the method outlined in paragraph 7. It should perhaps again be emphasized, however, that the use of a working curve in this way is only valid for subsequent measurements in which no pertinent experimental parameter has been changed since the working curve was obtained. This means, to be more specific, that such things as the emissivity of the projectile surface, the projectile velocity, the optical arrangement, and the characteristics of the detecting system must be held rigidly fixed.

24. It may be stated, in conclusion, that the present equipment appears capable of measuring projectile temperatures in excess of 150°C and eventually of determining the temperature <u>rise</u> of a projectile during flight. This would require (a) an initial temperature in excess of 150°C and (b) a duplication of the measuring equipment, the temperature being measured at each of two stations. The possibility of carrying out a program of this type is being investigated at the present time.

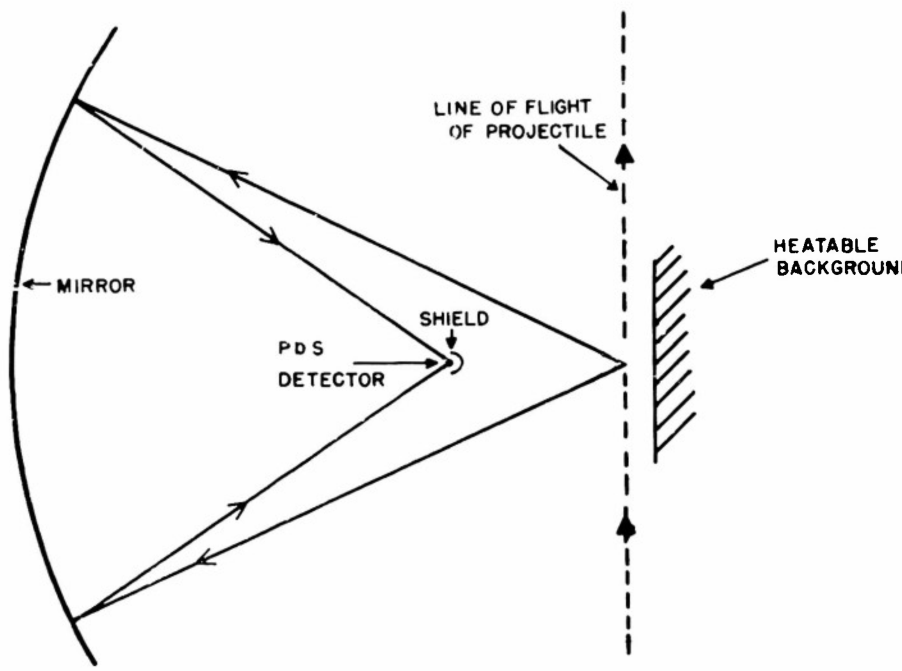


FIG. I DIAGRAM OF OPTICAL ARRANGEMENT

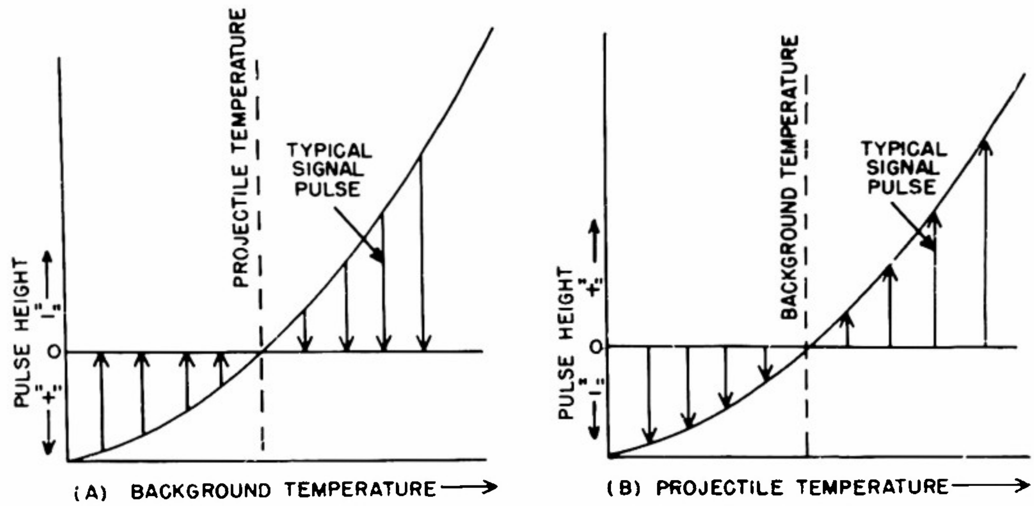
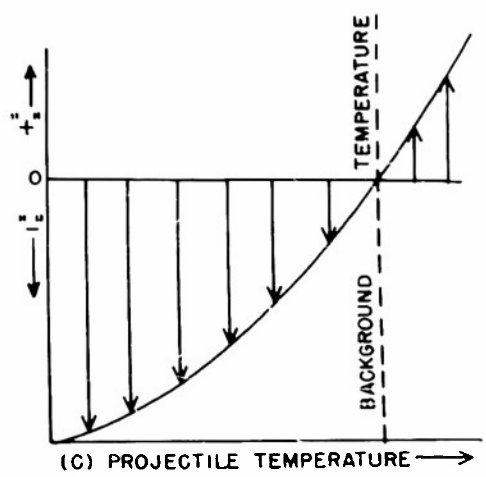


FIG. 2
SCHEMATIC REPRESENTION OF
WORKING CURVES



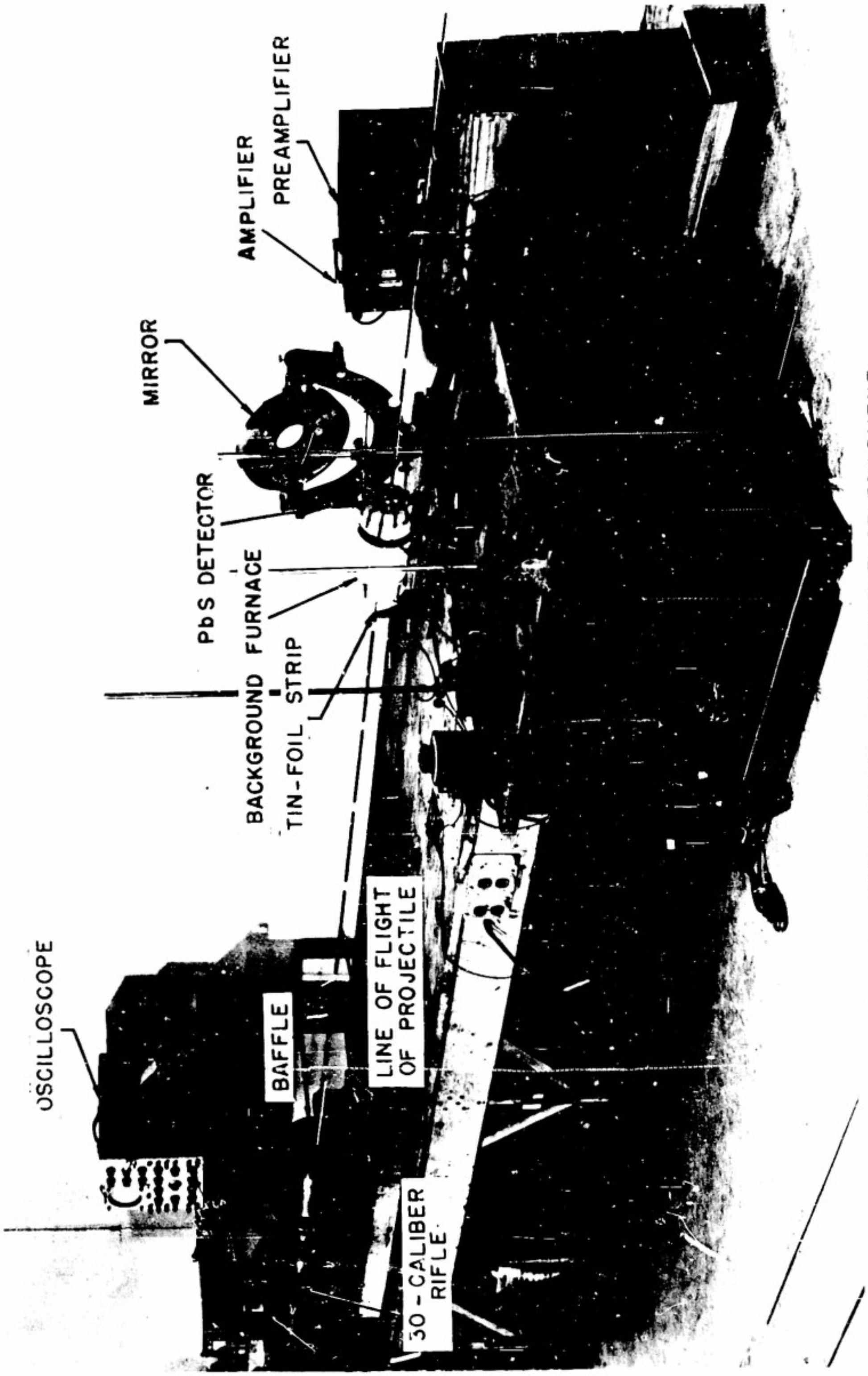


FIG. 3 EXPERIMENTAL ARRANGEMENT OF EQUIPMENT

FIG. 4 EXPERIMENTAL ARRANGEMENT OF EQUIPMENT

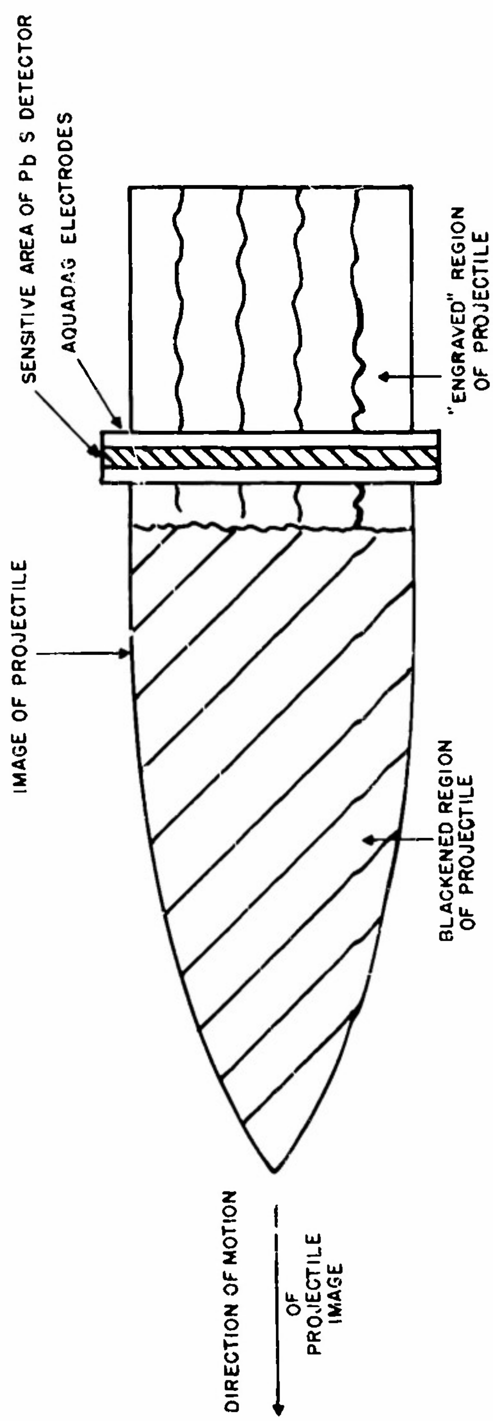


FIG.5
DIAGRAM SHOWING IMAGE OF PROJECTILE CROSSING SENSITIVE AREA OF Pb S DETECTOR

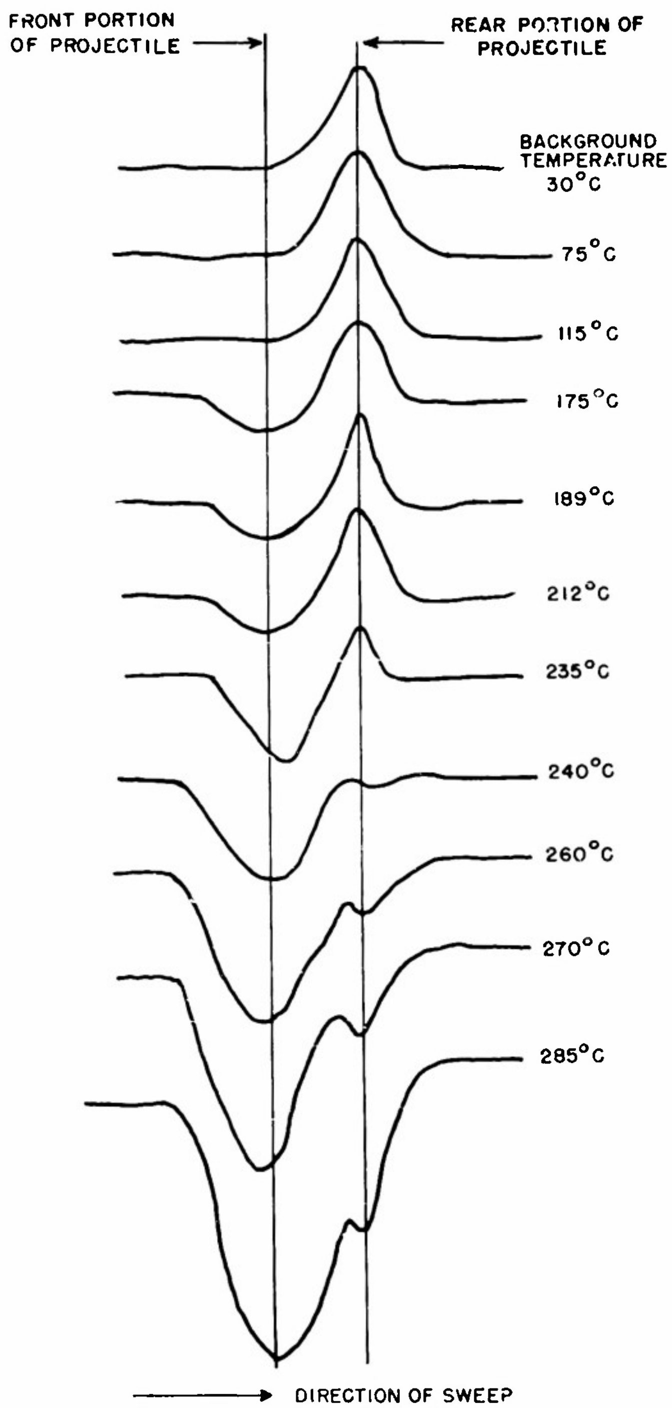


FIG. 6 TYPICAL SERIES OF OSCILLOSCOPE TRACES

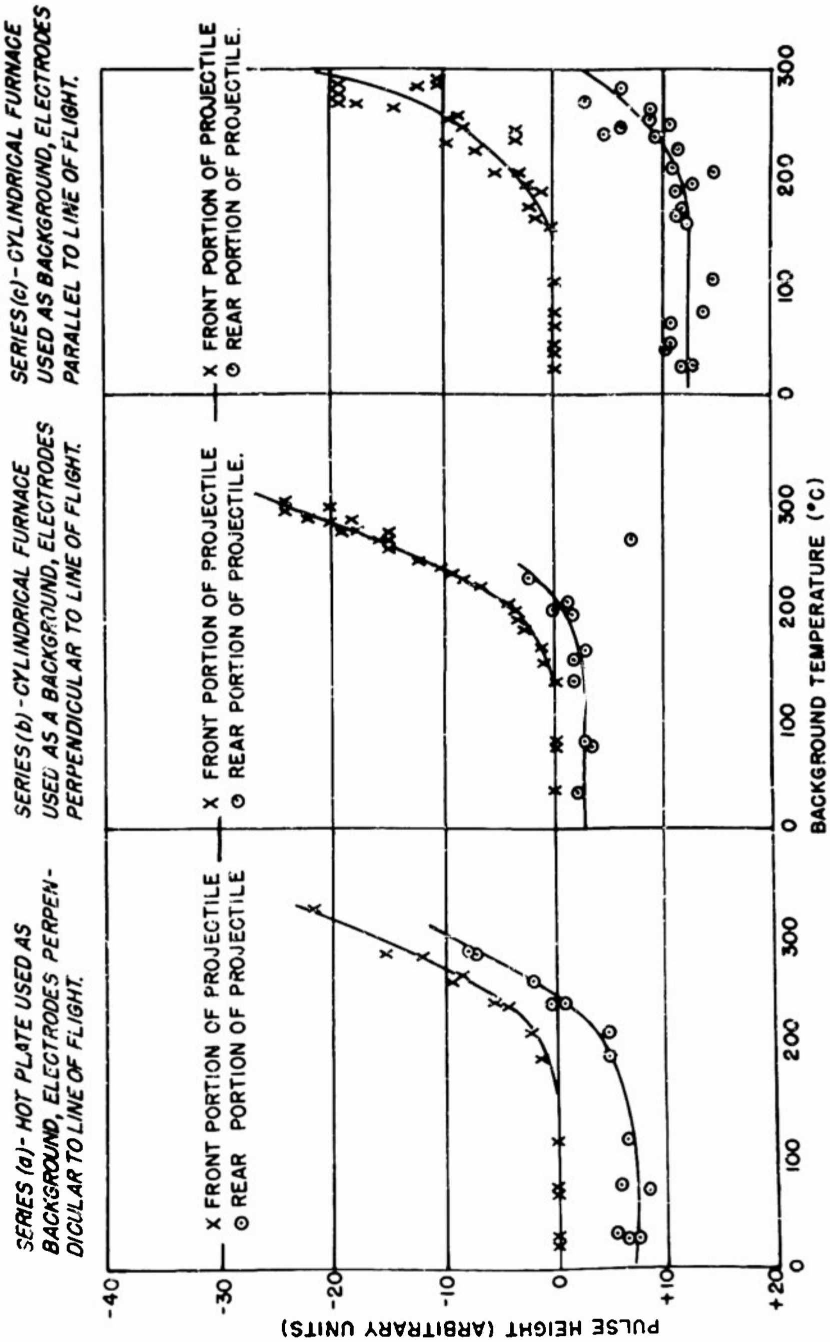


FIG. 7 WORKING CURVES OBTAINED WITH STANDARD 30-CALIBER PROJECTILES

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